Enhanced Pulse Compression in Nonlinear Fiber by a WDM Optical Pulse

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ABSTRACT

A new way to compress an optical pulse in a single-mode fiber is presented in this paper. By the use of the cross phase modulation (CPM) effect caused by the nonlinearity of the optical fiber, a shepherd pulse propagating on a different wavelength beam in a wavelength division multiplexed (WDM) single-mode fiber system can be used to enhance the pulse compression of a co-propagating primary pulse. Although CPM will not cause energy to be exchanged among the beams, but the pulse shapes on these beams can be altered significantly. For example, a one milliwatt peak power 10 ps primary pulse on a given wavelength beam may be compressed by a factor of as much as 25 when a co-propagating 10 ps shepherd pulse of peak power of 49 milliwatts on a different wavelength beam is similarly compressed. Results of a systematic study on this effect are presented in this paper. Furthermore, even when the primary pulse on a given wavelength beam has a peak power of much less than one milliwatt it can still be compressed by the same compression factor as a co-propagating shepherd pulse of peak power much larger than one milliwatt on a different wavelength beam as it undergoes compression. Through CPM, co-propagating pulses on separate beams appear to share the nonlinear effect induced on any one of the pulses on separate beams.

I. Introduction

In spite of the intrinsically small value of the nonlinearity coefficient in fused silica, due to low loss and long interaction length, the nonlinear effects in optical fibers made with fused silica cannot be ignored even at relatively low power levels [1]. This nonlinear phenomenon in fibers has been used successfully to generate optical solitons [2], to compress optical pulses [3], to transfer energy from a pump wave to a Stokes wave through the Raman gain effect [4], to transfer energy from a pump wave to a counter-propagating Stokes wave through the Brillouin gain effect [5], to produce four-wave mixing [6] and to dynamically shepherd pulses [7].

In a WDM system, the cross phase modulation (CPM) effects [8,9] caused by the nonlinearity of the optical fiber are unavoidable. These CPM effects occur when two or more optical beams co-propagate simultaneously and affect each other through the intensity dependence of the refractive index. This CPM phenomenon can be used to produce an interesting pulse shepherding effect to align the arrival time of pulses which are otherwise misaligned. This same CPM effect can also be used to produce highly compressed pulse on a different wavelength beam.

The usual soliton-effect compressor [3,10-13], which makes use of higher-order solitons supported by fiber as a result of interplay between self-phase modulation (SPM) and anomalous group-velocity dispersion (GVD), is well known. It is found here that the interplay between CPM and GVD may also provide similar pulse compression effect. The significant difference is that pulse compression can take place for pulses on a different wavelength beam. This means that the high power pulse on one wavelength beam may be used to provide high compression to a low power pulse on another wavelength beam.

The purpose of this paper is to provide detailed simulation results on this new type of pulse compression technique.

II. Formulation of the Problem

The fundamental equations governing M numbers of co-propagating waves in a nonlinear fiber including the CPM phenomenon are the coupled nonlinear Schrodinger equations [7,14]:

$$\frac{\partial A_j}{\partial z} + \frac{1}{v_{gj}} \frac{\partial A_j}{\partial t} + \frac{1}{2} \alpha_j A_j = \frac{1}{2} \beta_2 \frac{\partial^2 A_j}{\partial t^2} - \gamma_j \left(|A_j|^2 + 2 \sum_{m \neq j}^{M} |A_m|^2 \right) A_j$$

$$(j = 1,2,3, \cdots\cdots M) \tag{1}$$

Here, for the jth wave, $A_j(z,t)$ is the slowly-varying amplitude of the wave, v_{gj}, the group velocity, β_{2j}, the dispersion coefficient ($\beta_{2j} = dv_{gj}^{-1}/d\omega$), α_j, the absorption coefficient, and

$$\gamma_j = \frac{n_2 \ \omega_j}{c \ A_{eff}} \tag{2}$$

is the nonlinear index coefficient with A_{eff} as the effective core area and $n_2 = 3.2 \times 10^{-16}$ cm^2/W for silica fibers, ω_j is the carrier frequency of the jth wave, c is the speed of light, and z is the direction of propagation along the fiber.

Introducing the normalizing coefficients

$$\tau = \frac{t-(z/v_{g1})}{T_0}$$

$$d_{1j} = (v_{g1}-v_{gj})/v_{g1}v_{gj},$$

$$\xi = z/L_{D1}, \tag{3}$$

$$L_{D1} = T_0^2/|\beta_{21}|,$$

and setting

$$u_j(\tau,\xi) = (A_j(z,t)/\sqrt{P_{0j}})\ \exp(\alpha_j L_{D1}\xi/2) \tag{4}$$

$$L_{NLj} = 1/(\gamma_j P_{0j})$$

$$L_{Dj} = T_0^2/|\beta_{2j}| \tag{5}$$

gives

$$i\frac{\partial u_j}{\partial \xi} = \frac{\mathrm{sgn}(\beta_{2j})L_{D1}}{2L_{Dj}}\frac{\partial^2 u_j}{\partial \tau^2} - i\frac{d_{1j}}{T_0}L_{D1}\frac{\partial u_j}{\partial \tau}$$

$$-\frac{L_{D1}}{L_{NLj}}\left[\exp(-\alpha_j L_{D1}\xi)|u_j|^2 + 2\sum_{m\neq j}^{M}\exp(-\alpha_m L_{D1}\xi)|u_m|^2\right]u_j$$

$$(j = 1,2,3, \ldots\ldots M) \tag{6}$$

Here, T_0 is the pulse width, P_{0j} is the incident optical power of the jth beam, and d_{1j}, the walk-off parameter between beam 1 and beam j, describes how fast a given pulse in beam j passes through the pulse in beam 1. In other words, the walk-off length is

$$L_{W(1j)} = T_0/|d_{1j}|. \tag{7}$$

So, $L_{W(1j)}$ is the distance for which the faster moving pulse (say, in beam j) completely walked through the slower moving pulse in beam 1. The nonlinear interaction between these two optical pulses ceases to occur after a distance $L_{W(1j)}$. For cross-phase modulation (CPM) to take effect significantly, the group-velocity mismatch must be held to near zero.

It is also noted from Eq. (6) that the summation term in the bracket representing the cross-phase modulation (CPM) effect is twice as effective as the self phase modulation (SPM) effect for the same intensity. This means that the nonlinear effect of the fiber medium on a beam may be enhanced by the co-propagation of another beam with the same group velocity.

III. Numerical Solution

Equation (6) is a set of simultaneous coupled nonlinear Schrodinger equations which may be solved numerically by the split-step Fourier method, which was used successfully earlier to solve the problem of beam propagation in complex fiber structures, such as, the fiber couplers [15], and to solve the thermal blooming problem for high energy laser beams [16]. According to this method, the solutions may be advanced first using only the nonlinear part of the equations. And then the solutions are allowed to advance using only the linear part of Eq. (6). This forward stepping process is repeated over and over again until the desired destination is reached. The Fourier transform is accomplished numerically via the well-known Fast Fourier Transform Technique. Due to the large dynamic range of the pulse width, a mesh size of 2048 with $\Delta\tau = 0.01$ was used.

Using the above approach, the evolution of all the pulses on all the co-propagating WDM beams as they propagate down the fiber may be obtained. It was through these numerical computations that we discovered the interesting pulse shepherding and beam compression effects [7]. As expected these effects only exist when group-velocity mismatch for the interested beams is negligible. In other words, there is no walk-off [7,14] among the interested beams. This can be accomplished through proper tailoring of the dispersion characteristics of a single-mode fiber [17].

Consider now the evolution of two single soliton pulses on two co-propagating beams whose operating wavelengths are separated by $\Delta\lambda > 4$ nm. For this case, the four wave mixing effect is negligible. Let us label the first pulse as the primary (P) pulse and the second pulse as the shepherd (S) pulse. The soliton number N_j for the pulse on the jth beam is defined as

$$N_j^2 = L_{Dj}/L_{NLj}.$$

Furthermore, we assume that there is negligible walk-off, i.e.,

$$d_{1j} = \text{walk-off parameter between beam \#1 and beam \#j}$$
$$= v_{g1} - v_{gj} = 0,$$

and there is no loss, i.e.,

$$\alpha_j = \text{attenuation or absorption of beam j in fiber}$$
$$= 0.$$

The neglect of fiber loss is justified since the fiber lengths typically employed are only a small fraction of the absorption length ($\alpha_j L << 1$). Strictly speaking, for multiple interacting beams, there is no condition under which solitons may exist even if the fiber is lossless. However, numerical simulation shows that significant pulse compression still exists for these interacting pulses.

IV. Discussion of the Results

Shepherd pulse and primary pulse are all in anomalous dispersion region

For solitons propagating on a single beam in silica fibers, pulse compression is experienced when N, the soliton order, is larger than 1 [8]. This effect is due to the interaction of SPM (Self-Phase Modulation) and anomalous GVD (Group-Velocity Dispersion) during propagation. When two aligned pulses, one called the primary pulse and the other called the shepherd pulse, on two different wavelength beams co-propagate in a single-mode silica fiber, compression of both pulses occurs due to the interaction of CPM (Cross-Phase Modulation) of these two pulses and anomalous GVD during propagation.

A. Initial pulse widths are identical

Computer simulation results are shown in Fig. 1 through Fig. 4 for co-propagating pulses with identical initial pulse-width. Both pulses are in the anomalous GVD regime. In Fig. 1 the maximum amount of compression experienced by both pulses, the primary (P) pulse and the shepherd (S) pulse, are plotted against the soliton order N_s for the shepherd (S) pulse for various cases of the primary (P) pulse with the soliton order N_p. The amount of compression is expressed by the compression factor F_c, which is defined as [3]

$$F_c = T_{FWHM} / T_{COMP} ,$$

where the subscript FWHM means full width at half maximum for the pulse and the subscript COMP means FWHM of the compressed pulse. It is seen that, in the absence of the shepherd (S) pulse, i.e., $N_s = 0$, the primary (P) pulse under-goes the well-known soliton compression process for a single soliton pulse for soliton number $N > 1$. As expected, the primary (P) pulse retains its shape when $N_p = 1$. But, when a co-propagating shepherd (S) pulse is present, both pulses undergo the same compression even if N_p is not equal to N_s or if $N_s < 1$ or if $N_s << 1$. Furthermore, the amount of compression is always larger than that achievable by a single stand-alone pulse.

For $N_s > N_p$, the shepherd pulse helps to compress the primary pulse further, especially when soliton number for the primary pulse is near unity. For example, as N_s varies from 1 to 7, the pulse width of the $N_p = 1$ primary pulse can be compressed by the shepherd pulse by a factor of 27, while the pulse width of the $N_p = 2$ primary pulse will be compressed by a factor of 7. For an $N_p = 5$ primary pulse, its pulse width will be reduced by a factor of only 2.2 as N_s varies from 1 to 7. In other words, the weaker is the intensity of the primary pulse the more its pulse width will be compressed by the presence of a co-propagating high intensity shepherd pulse. Figure 2 gives an illustration of the evolution of the pulse shapes of the primary and shepherd pulses for the case where $N_s = 7$ and $N_p = 1$.

For $N_s < N_p$, the shepherd pulse still helps to compress the primary pulse further, but the effect is much more moderate. For example, as N_s varies from 0 to 2, the pulse width of the $N_p = 2$ primary pulse is compressed by a factor of 2.4, while the pulse width of the $N_p = 5$ primary pulse will be compressed by a factor of only 2 as N_s varies from 0 to 5. This means that to effectively enhance the pulse compression of a primary pulse, higher intensity shepherd pulse must be used. Figure 3 shows evolution of the pulse shapes of the primary and shepherd pulses for the case where $N_s = 2$ and $N_p = 5$.

It is known that a single pulse with $N < 1$, no pulse compression will occur. Hence a $N_p < 1$ primary pulse traveling alone or a $N_s < 1$ shepherd pulse traveling alone will not experience any pulse compression. This is no longer true when these pulses co-propagate in the fiber. Even when $N_p + N_s < 1$, a slight pulse compression may still be observed for both the primary pulse and the secondary pulse. This is caused by the nonlinearity of the fiber medium. One also notes that when $N_p << 1$ and $N_s > 1$, pulse compression will be experienced by both the primary and the shepherd pulses. Same degree of pulse compression will occur on the primary pulse even when $N_p << 1$. The degree of pulse compression for the primary pulse or the shepherd pulse is governed by the $N_s > 1$ shepherd pulse.

Figure 4 shows the normalized optimum fiber length z_{opt}/z_{0p} for the primary pulse as a function of N_s for various fixed values of N_p, where z_{opt} is the optimum fiber length in kilometers for the primary or shepherd pulse when it experiences maximum pulse compression and $z_{0p} = (\pi/2)L_{Dp}$. Here, L_{Dp} is dispersion length for the primary pulse defined in Eq. (5). It is of interest to note that z_{opt} for the primary pulse occurs at the same location or very near the same location as that for the shepherd pulse. This means that maximum pulse compression for the primary pulse and that for the shepherd pulse occur at the same location and at the same time. For high values of N_s, this normalized optimum fiber length can be much smaller than unity, indicating that the maximum pulse compression could occur at a length many times smaller than the dispersion length. Using the following physical parameters as an example:

β_2 = dispersion coefficient = -2.0 ps^2/km

λ_1 = operating wavelength of beam #1 = 1.552 μm

λ_2 = operating wavelength of beam #2 = 1.548 μm

γ = nonlinear index coefficient = 20 $W^{-1}km^{-1}$

P_0 = incident power of each beam = 1 mW

α = attenuation or absorption of each beam in fiber

= 0 dB/km

v_g = group velocity of the beam = 2.051147 x 10^8 m/sec

d_{1j} = walk-off parameter between beam #1 and beam #j

= $v_{g1} - v_{gj}$ = 0 (no walk-off)

T_0 = pulse width = 10 ps,

one has

L_{Dp} = 50 km.

Take the case of N_p = 5 and N_s = 7, one finds z_{opt}/z_{0p} = 0.04 from Fig. 4. This means maximum pulse compression can occur in a fiber with length of only 2.0 km long. For higher values of N_p and/or N_s, this length can be made even shorter.

B. Initial pulse widths are not identical

We have also investigated the case where the pulse width of the primary pulse and that of the shepherd pulse are not identical. Let us consider the case where a primary pulse has an initial intensity of N_p = 1 and a shepherd pulse has an initial intensity of N_s = 9. It was assumed that the pulse width of the shepherd pulse is varied from the same to several times (3-5 times) wider than that of the primary pulse. Our computer simulation shows that the primary pulse is similarly compressed for all the above cases. In other words, varying the pulse width of the shepherd pulse does not appear to affect the minimum pulse width achievable for the primary pulse although the distance required to gain this minimum pulse width for the primary is increased as the pulse width of the shepherd pulse is increased. The amount of pulse compression for the primary pulse is governed by the intensity of the accompanying shepherd pulse.

It is observed that, for the broad shepherd pulse, only the central portion of the shepherd pulse that overlaps the primary pulse is significantly affected and undergoes compression.

This simulation shows that the broader shepherd pulse with high intensity appears to enhance (or increase) the strength of the nonlinear coefficient of the fiber medium for the primary pulse so as to enhance the pulse compression effect experienced by the primary pulse. This means that there is a way to dynamically increase the nonlinear effect of the medium through the addition of a broad, high intensity shepherd pulse. The amount of enhancement and the duration are controlled by the intensity and the pulse width of the shepherd pulse. The nonlinear effect of the medium is transferred to the primary pulse through the CPM effect.

Let us now investigate the case where the intensity of the narrow shepherd pulse is much higher than that of the broad primary pulse. In this simulation, the initial intensity of the narrow shepherd pulse is taken to be $N_s = 9$ and that of the broad primary pulse is $N_p < 1$. Both pulses undergo compression. The degree of compression is mostly governed by the high intensity narrow shepherd pulse. For example, at the maximum compression distance, the shepherd pulse is compressed by a factor of approximately 16, while a narrow pulse with the same compressed pulse width as that of the shepherd pulse appears to have been generated on top of the broad small intensity primary pulse which appears as the pedestal for the narrow pulse.

It is noted here that what has been described above has practical significance. This scheme provides a practical pure optical way of generating very narrow bits on different wavelength streams for the bit-parallel data format.

Shepherd pulse is in normal dispersion region and primary pulse is in anomalous dispersion regime

It is known that pulse compression of a single pulse in a fiber occurs because of the interaction of the nonlinear effect and the anomalous GVD effect [8]. This interaction also gives birth to the possible existence of a soliton pulse with $N = 1$. The above simulation results show that when a shepherd pulse is added as a co-propagating companion primary pulse, enhancement of pulse compression of the primary pulse is observed. It is of interest to learn if this pulse compression enhancement of the primary pulse still exists if the shepherd pulse is launched on a beam whose wavelength falls in the normal GVD regime. This computer experiment has been carried out. In this experiment N_p is set to unity with β_{2p} = -2 while N_s is set to 9 with β_{2s} = +2. It is expected that without the shepherd pulse, the primary pulse is a soliton pulse which will retain its shape without pulse compression or pulse spreading as it propagates down the fiber. Also, without the primary pulse, the high amplitude shepherd pulse in the normal dispersion regime is expected to propagate without experiencing pulse compression. When both of these pulses copropagate on two separate beams, pulse shepherding effect is observed but no pulse compression is observed.

If N_p and N_s are both set to be 9, the high amplitude of the primary pulse in the anomalous dispersion regime produces large pulse compression, but the degree of pulse compression (i.e., the narrowness of the compressed pulse) is not influenced by the presence of the high amplitude shepherd pulse in the normal dispersion regime. On the other hand, a very significant dip appears in the center of the shepherd pulse in the normal dispersion regime breaking the original single shepherd pulse into two pulses. This is very different than the case where both primary and shepherd pulses are in the anomalous dispersion region. There both pulses undergo compression.

Shepherd pulse and primary pulse are all in normal dispersion region

When both shepherd and primary pulses are in the normal dispersion region, no pulse compression occurs. Pulses tend to congregate towards region of higher induced index of refraction.

Summary of the above discussion

The interaction between two separate pulses copropagating on two different wavelength beams in a single mode fiber is studied in detail. It is shown that the cross phase modulation (CPM) effect can be use effectively to provide another way to generate pulse compression in the anomalous dispersion region of a single mode fiber. Due to the nonlinearity of the fiber medium, a slight pulse compression still occurs when the sum of the soliton numbers for the two beams is less than unity.

A more complex interaction is observed when one of the pulses is propagating in the normal dispersion region. The pulse in the normal dispersion region is seen to be broken up by the compression of the high soliton number pulse in the anomalous dispersion region. It also appears that if the pulse in the normal dispersion region is very broad compared with the high intensity narrow pulse in the anomalous dispersion region, a dark soliton-like pulse can be generated on top of the broad pulse in the normal dispersion region while the pulse in the anomalous dispersion region undergoes the usual pulse compression. Figure 5 is introduced to illustrate the evolution of the two propagating pulses when they exist in various different combinations of the dispersion regions.

It should be noted that the dispersion region in which the beam resides (i.e., where the beam wavelength resides) is all important in determining to behavior of the pulse on that beam even in the presence of a copropagating pulse on a different wavelength beam. The copropagating shepherd pulse, through the cross-phase modulation effect due to the Kerr index nonlinearity, provides an additional phase retardation to the primary pulse as it travels down the fiber. In other words, additional frequency chirp (in addition to that caused by self-phase modulation) is added to the primary pulse by the copropagating shepherd pulse.

This 'chirped' primary pulse is acted upon by the fiber's dispersion to yield the expected behavior. For example, if the primary pulse is on a beam whose wavelength is in the anomalous dispersion region (negative GVD region) and if the 'chirp' caused by self- and cross-modulation effect is high enough, the leading half of the pulse containing the lowered frequencies, will be retarded, while the trailing half, containing the higher frequencies, will be advanced, and the primary pulse will tend to collapse upon itself resulting in pulse narrowing or pulse compression. (See Fig. 5 (B) and (C).)

On the other hand, if the primary pulse is on a beam whose wavelength is in the normal dispersion region (positive GVD region), the presence of a copropagating shepherd pulse on a different wavelength beam induces a dark-soliton-like behavior for the primary pulse, confirming the fact that the dispersive region in which the wavelength of the beam resides determines the propagation characteristic of that pulse. In contrast with the bright soliton case, dark soliton possesses a nontrivial phase profile which is a function of time, resulting in a rapid dip in the intensity of a broad pulse. (See Fig. 5 (A) and (D).)

Investigation was also carried out for the interaction of pulses on more than two beams. As many as ten simultaneously propagating pulses on ten separate beams, with one carrying the shepherd pulse, were used. It was found that a single large amplitude shepherd pulse could similarly and simultaneously affect the other nine small amplitude pulses. Evolution of each of the small amplitude pulses depended mainly on the interaction of that pulse with the large amplitude shepherd pulse according to the manner discussed above for the two beam interaction case. Through CPM, co-propagating pulses on separate beams appear to share the nonlinear effect induced on any one of the pulses on separate beams.

This investigation shows that for a wavelength division multiplexed (WDM) system, one shepherd pulse can cause the compression of all the other wavelength pulses, thereby, improving their pulse widths as well as the separation of different pulses. Furthermore, since the longer wavelength pulses are compressed at rate different from the shorter wavelength pulses, one may conceivably make all pulses have the same time width which may make detection and discrimination easier to accomplish.

V. Conclusion

A new way to compress bright or dark pulse is found. The nonlinear cross phase modulation (CPM) effect is used to accomplish this on two or more co-propagating pulses on two or more wavelength division multiplexed (WDM) beams in a single-mode fiber. Numerical simulation shows that the effectiveness of compression is similar to that displayed by a single higher order soliton pulse propagating in a single beam. That this CPM effect can be used to compress pulses whose amplitudes are much less than unity (the traditional soliton number for a single beam) as long as a co-propagating pulse on a WDM beam undergoes compression, should be noted.

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Figure Captions

Figure 1. Compression factor (F_c) for varies soliton values (N_p) of a primary pulse (P) as a function of soliton values (N_s) of a co-propagating shepherd pulse (S). The compression factor for the primary pulse is the same as the compression factor for the shepherd pulse. Initial pulse width for the primary pulse and that for the shepherd pulse are identical. The compression factor F_c is defined as the ratio between the full width at half maximum for the initial uncompressed pulse and that for the final compressed pulse.

Figure 2. An illustration of the evolution of the shepherd pulse and the primary pulse for $N_s = 7$ and $N_p = 1$. Both pulses are in the anomalous dispersion region. Power amplitude, $|u|^2$, is plotted in each frame. Highest power amplitude in each frame is normalized to unity. The initial power amplitude for the shepherd pulse is 49 ($N_s = 7$) and that of the primary pulse is 1 ($N_p = 1$). The final power amplitude for the shepherd pulse is 71.2 and that of the primary pulse is 2.15. The number along the horizontal abscissa refers to the normalized distance from the starting point of the fiber; in other words, when the normalized distance is 3, the distance is $3(z_{opt}/z_o)z_o/5$ where $z_o = (\pi/2)L_{Ds}$ and L_{Ds} is the dispersion length of the shepherd pulse. z_{opt} is the optimum fiber length in kilometers for the shepherd pulse when it experiences maximum pulse compression.

Note that both pulses with different initial soliton numbers are similarly compressed and the degree of compression for both pulses is higher than that experienced by each pulse when propagating alone. The dispersion coefficients, β_{2s} and β_{2p}, have units of (ps^2/km). All other numbers in the figure are dimensionless.

Figure 3. An illustration of the evolution of the primary pulse and the shepherd pulse for $N_s = 2$ and $N_p = 5$. Both pulses are in the anomalous dispersion region. Power amplitude, $|u|^2$, is plotted in each frame. Highest power amplitude in each frame is normalized to unity. The initial power amplitude for the shepherd pulse is 4 ($N_s = 2$) and that of the primary pulse is 25 ($N_p = 5$). The final power amplitude for the shepherd pulse is 6.96 and that of the primary pulse is 35.1. The number along the horizontal abscissa refers to the normalized distance from the starting point of the fiber; in other words, when the normalized distance is 3, the distance is $3(z_{opt}/z_o)z_o/5$ where $z_o = (\pi/2)L_{Ds}$ and L_{Ds} is the dispersion length of the shepherd pulse. z_{opt} is the optimum fiber length in kilometers for the shepherd pulse when it experiences maximum pulse compression. Note that both pulses with different initial soliton numbers are similarly compressed and the degree of compression for both pulses is higher than that experienced by each pulse when propagating alone. The dispersion coefficients, β_{2s} and

β_{2p}, have units of (ps^2/km). All other numbers in the figure are dimensionless.

Figure 4. Normalized optimum fiber length as a function of N_s for various fixed values of N_p. $z_o = (\pi/2)L_{Ds}$ and L_{Ds} is the dispersion length of the shepherd pulse. z_{opt} is the optimum fiber length in kilometers for the shepherd pulse when it experiences maximum pulse compression.

Figure 5. Evolution of two propagating pulses in various different dispersion regions. Initial pulse amplitude of primary pulse (pulse 1) is $N_p = 0.1$ and initial pulse amplitude of shepherd pulse (pulse 2) is $N_s = 3$. Initial pulse width of primary pulse (pulse 1) is 3 times the initial pulse width of shepherd pulse (pulse 2).

(A) Primary pulse 1 and shepherd pulse 2 are both in the normal dispersion region ($\beta_2 = +2$).

(B) Primary pulse 1 and shepherd pulse 2 are both in the anomalous dispersion region ($\beta_2 = -2$).

(C) Primary pulse 1 is in the anomalous dispersion region ($\beta_2 = -2$) and shepherd pulse 2 is in the normal dispersion region ($\beta_2 = +2$).

(D) Primary pulse 1 is in the normal dispersion region ($\beta_2 = +2$) and shepherd pulse 2 is in the anomalous dispersion region ($\beta_2 = -2$).

Power amplitude, $|u|^2$, is plotted in each frame. Highest power amplitude in each frame is normalized to unity. The initial power amplitude for the shepherd pulse is 9 ($N_s = 3$) and that of the primary pulse is 0.01 ($N_p = 0.1$). The final power amplitude for the shepherd pulse is (A)=6.59, (B)=14.8, (C)=6.59, (D)=14.8 and that of the primary pulse is (A)=0.0116, (B)=0.0317, (C)=0.0195, (D)=0.0121. The number along the horizontal abscissa refers to the normalized distance from the starting point of the fiber; in other words, when the normalized distance is 3, the distance is $3(z_{opt}/z_o)z_o/5$ where $z_o = (\pi/2)L_{Ds}$ and L_{Ds} is the dispersion length of the shepherd pulse. z_{opt} is the optimum fiber length in kilometers for the shepherd pulse when it experiences maximum pulse compression. The dispersion coefficients, β_{2s} and β_{2p}, have units of (ps^2/km). All other numbers in the figure are dimensionless.

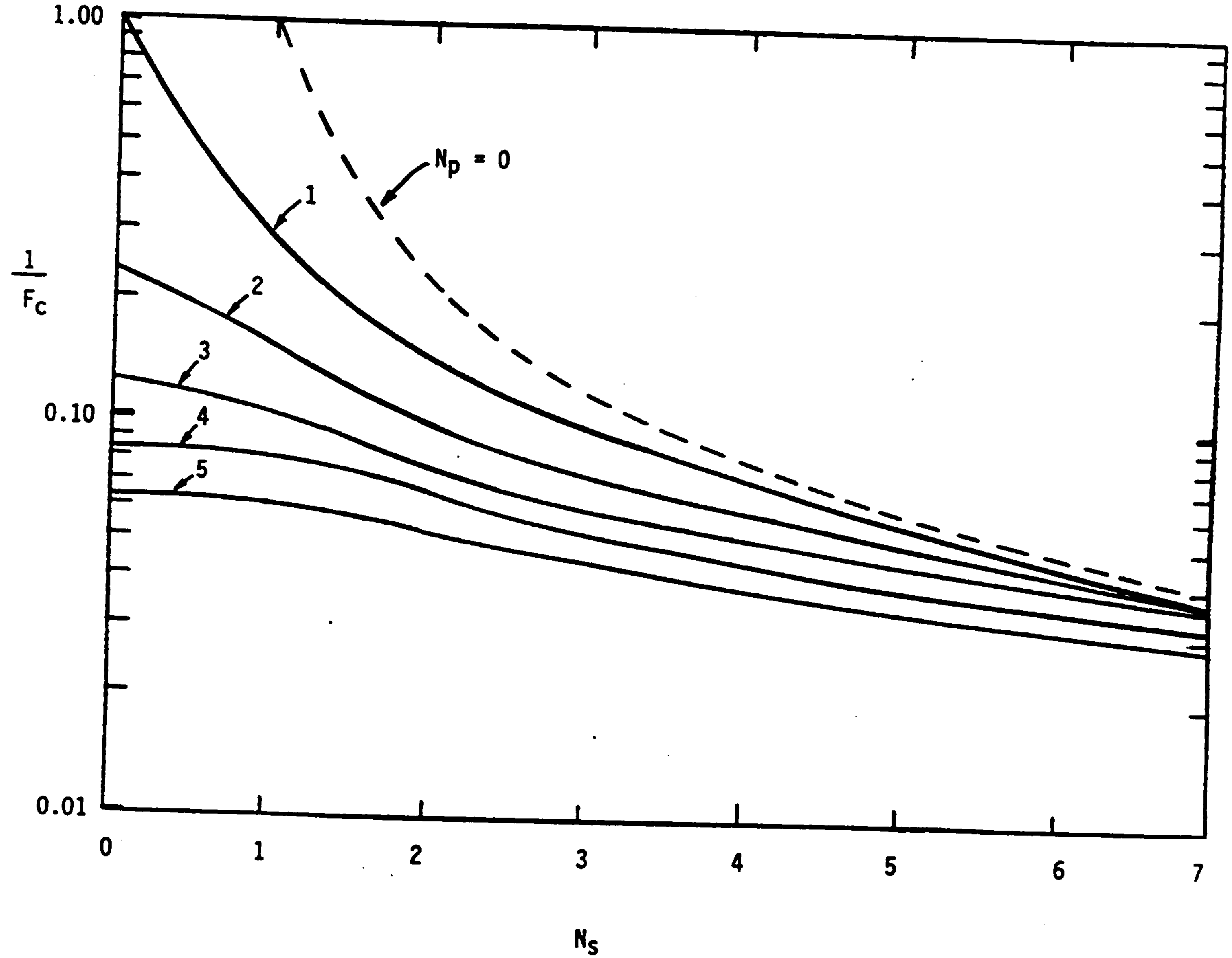

Figure 1
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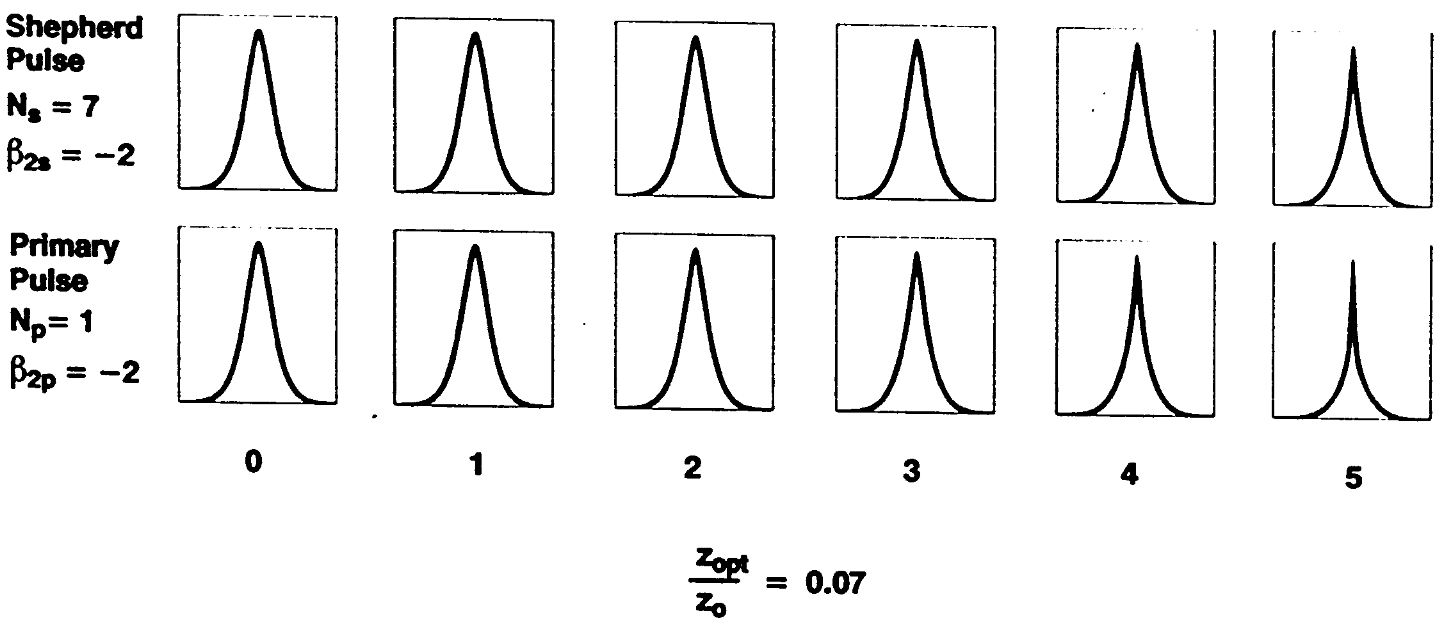
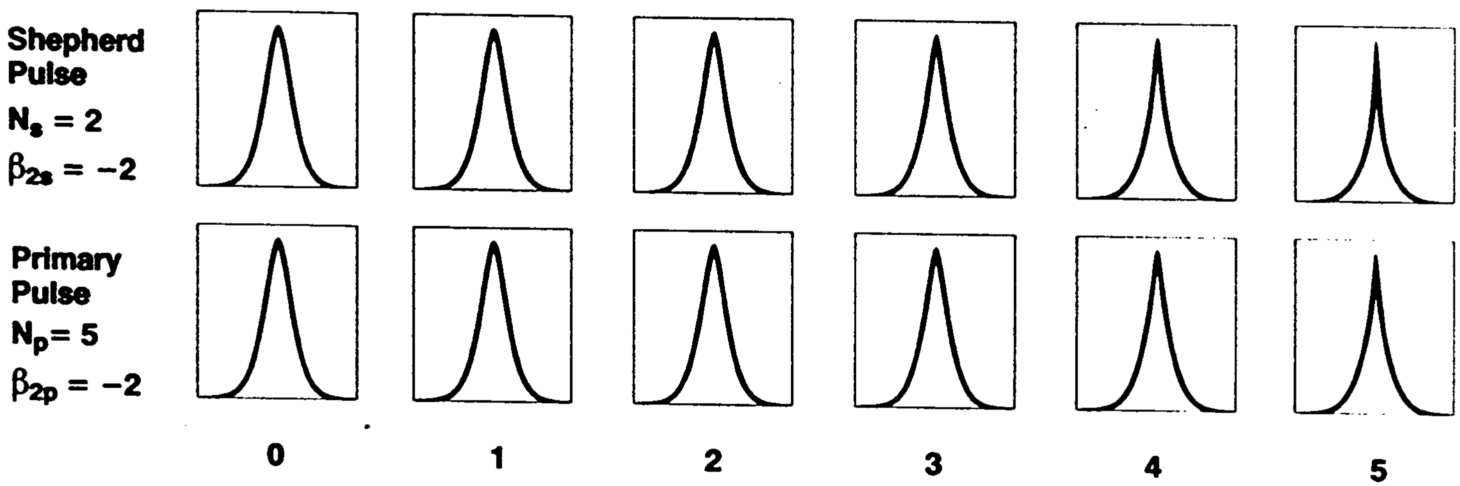


Figure 2
Yeh and Bergman
EG6312



$$\frac{z_{opt}}{z_o} = 0.085$$

Figure 3
Yeh and Bergman
EG6312

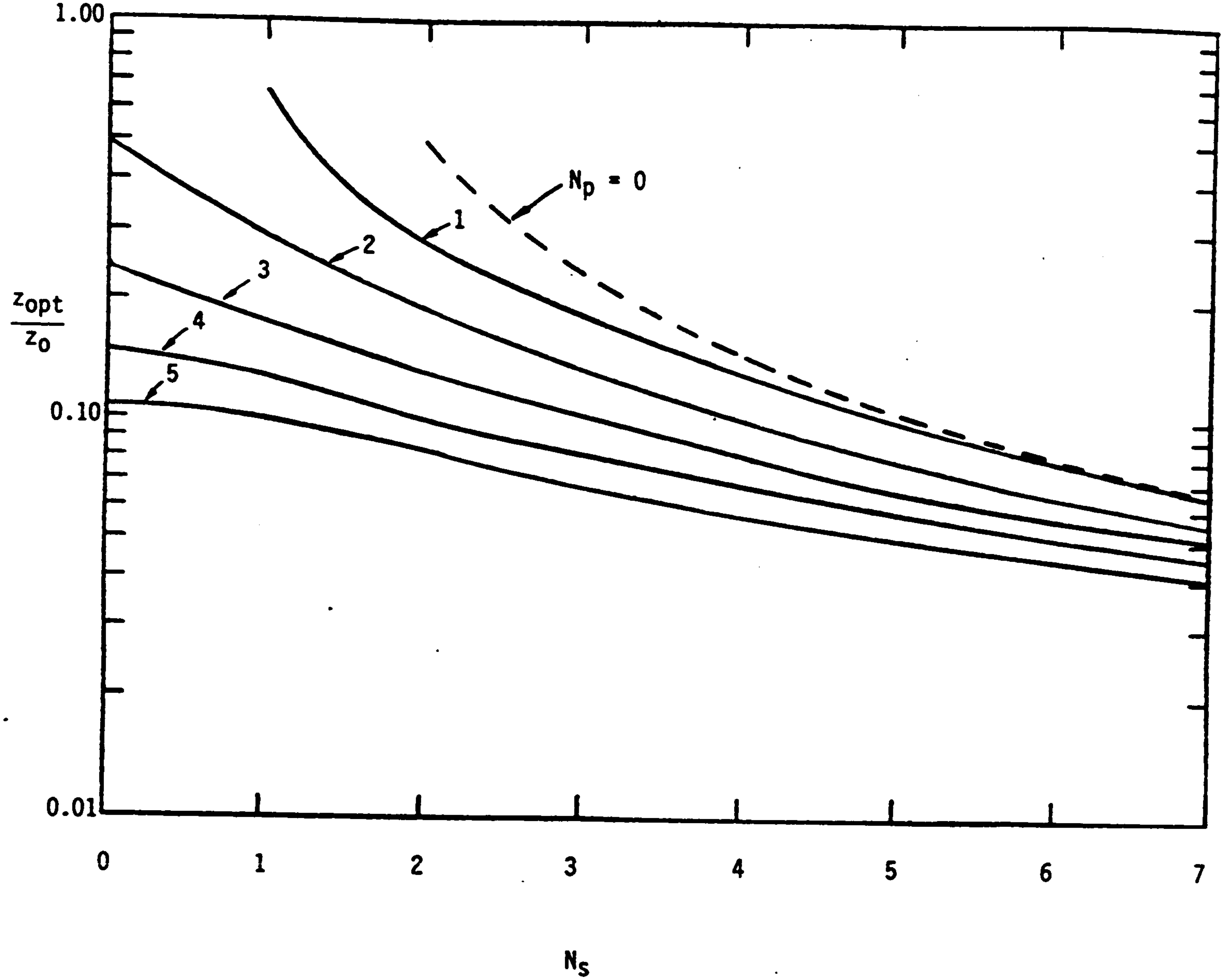
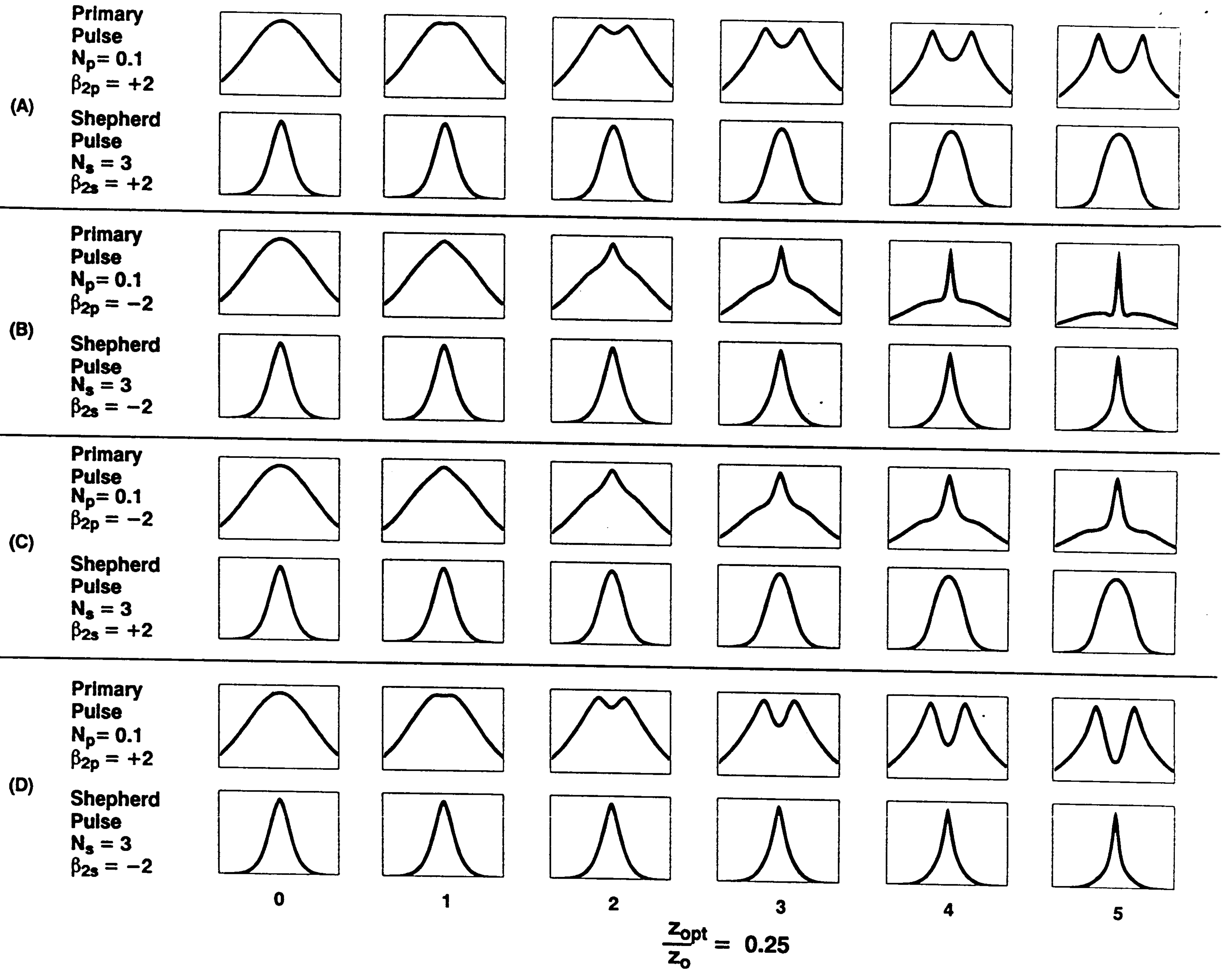


Figure 4
Yeh and Bergman
EG6312



(A)
Primary Pulse
$N_p = 0.1$
$\beta_{2p} = +2$
Shepherd Pulse
$N_s = 3$
$\beta_{2s} = +2$
(B)
Primary Pulse
$N_p = 0.1$
$\beta_{2p} = -2$
Shepherd Pulse
$N_s = 3$
$\beta_{2s} = -2$
(C)
Primary Pulse
$N_p = 0.1$
$\beta_{2p} = -2$
Shepherd Pulse
$N_s = 3$
$\beta_{2s} = +2$
(D)
Primary Pulse
$N_p = 0.1$
$\beta_{2p} = +2$
Shepherd Pulse
$N_s = 3$
$\beta_{2s} = -2$
0
1
2
3
4
5
$\frac{Z_{opt}}{Z_o} = 0.25$